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MONOLITHIC F-16 UNIFORM THICKNESS STRETCHED ACRYLIC CANOPY TRANSPARENCY PROGRAM

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12122 Western Avenue
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NOTICE

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This report documents the successful efforts to manufacture a subscale stretched acrylic canopy transparency of near uniform thickness. The report also provides the results of high temperature acrylic tensile tests, simple geometry forming tests and finite element computer models.

FOREWORD

The effort reported herein was conducted by Swedlow, Inc., located in Garden Grove, California, and was partially funded under Air Force Contract F33615-81-C-3416, amendment P00003. The Air Force administrative direction was provided by Lt. Dale Crocker and Mr. Ralph Speelman, AFWAL/FIEA.

The work described herein was conducted during the period September 1982 through September 1983. The principle investigator and project manager at Swedlow was Mr. Rick Hopkins and the person who conducted the forming experiments was Ms. Brooke Hall. Other persons who significantly contributed to the program success were Mr. Dave Holdridge, Manager of Design Engineering; Mr. Gene Nixon, Vice President of Engineering; and Dr. William Fischer, Corporate Vice President of Technology.

In addition to those listed above, the author wishes to acknowledge the contributions of Dr. Michael Burke of MARC Analysis Research Corporation in Palo Alto, California. Dr. Burke developed the necessary MARC code modifications and performed the finite element models.

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SECTION I

INTRODUCTION

The objective of this project was to demonstrate the feasibility of producing a uniform thickness aircraft canopy through subscale forming experimentation. This work was considered necessary before full scale fabrication of uniform thickness canopies having a complex curvature could be undertaken.

Aircraft canopies are normally of compound curvature shape. Generally they are made from constant thickness sheet stock which, when thermoplasticly formed, produces the required configuration. This shape, combined with the process used in its development, results in a nonuniform thinning of material. Thinning is greatest in the region most highly strained during forming.

For those canopies which are highly compound curved, like the F-16 aircraft canopy, thinning can be considerable. In many cases this non-uniform thickness is undesirable and may result in weight and performance penalties. A uniform thickness canopy or one in which the thickness is locally controlled would be beneficial.

One disadvantage of uncontrolled thinning of canopies is illustrated by the requirement to defeat bird strikes. The required thickness of a canopy necessary to resist these impacts is a function of the critical point of impact. In the case of the F-16 aircraft this critical impact point is in a high strain and therefore thinned region. Because of its geometry, the canopy is thicker than necessary in regions away from the critical point, and a substantial weight penalty occurs. The uniform thickness canopy would be advantageous, and locally controlled thickness would be preferred in order to minimize the weight of the canopy.

Although the study of uniform thickness canopies could have been conducted using almost any shape, that of the F-16 was selected for this project. In addition, the study concentrated on the forming characteristics of biaxially stretched acrylic material, even though the concepts apply to other thermoplastic materials. It should also be noted that the study of uniform thickness generating methods is applicable to the more general condition of controlled thickness.

Selection of the F-16 canopy and stretched acrylic material for this study was based upon its complex shape and perceived long range needs. Presently F-16 canopies are a multi-ply laminate construction consisting of polycarbonate and acrylic. Analysis has indicated that a uniform thickness stretched acrylic canopy for the F-16 could satisfy all design requirements including bird impact resistance at a weight comparable to that of the present composites, and with a greatly superior life.

Application of uniform thickness technology to the F-16 aircraft canopy could provide the means whereby the Air Force's goal of utilizing the most cost effective canopy transparency (while retaining specification

optics and structural requirements) could be met. Such a canopy for the F-16 could provide the following values:

- Reduced acquisition costs (about half of current part costs).
- Improved optical quality.
- Improved durability.

In order to demonstrate the concept of producing a uniform thickness canopy, both analytical and experimental actions were simultaneously undertaken. Analytical work was based on finite element modeling of the forming process. Experimental work was based on forming trials. Both of these activities were structured such that simple geometric forms were dealt with prior to advancing to the complex shape of the F-16 canopy.

The program was accomplished in two phases. In phase I, Swedlow investigated acrylic material properties at forming temperatures, conducted ideal geometry forming experiments, and modeled these experiments with finite element analysis. Phase II consisted of forming 1/4 scale models of the F-16 transparency shape. Two sets of F-16 subscale canopy parts were delivered to the US Air Force following this effort. A stretched acrylic canopy model of virtually uniform thickness is shown in Figure 1.

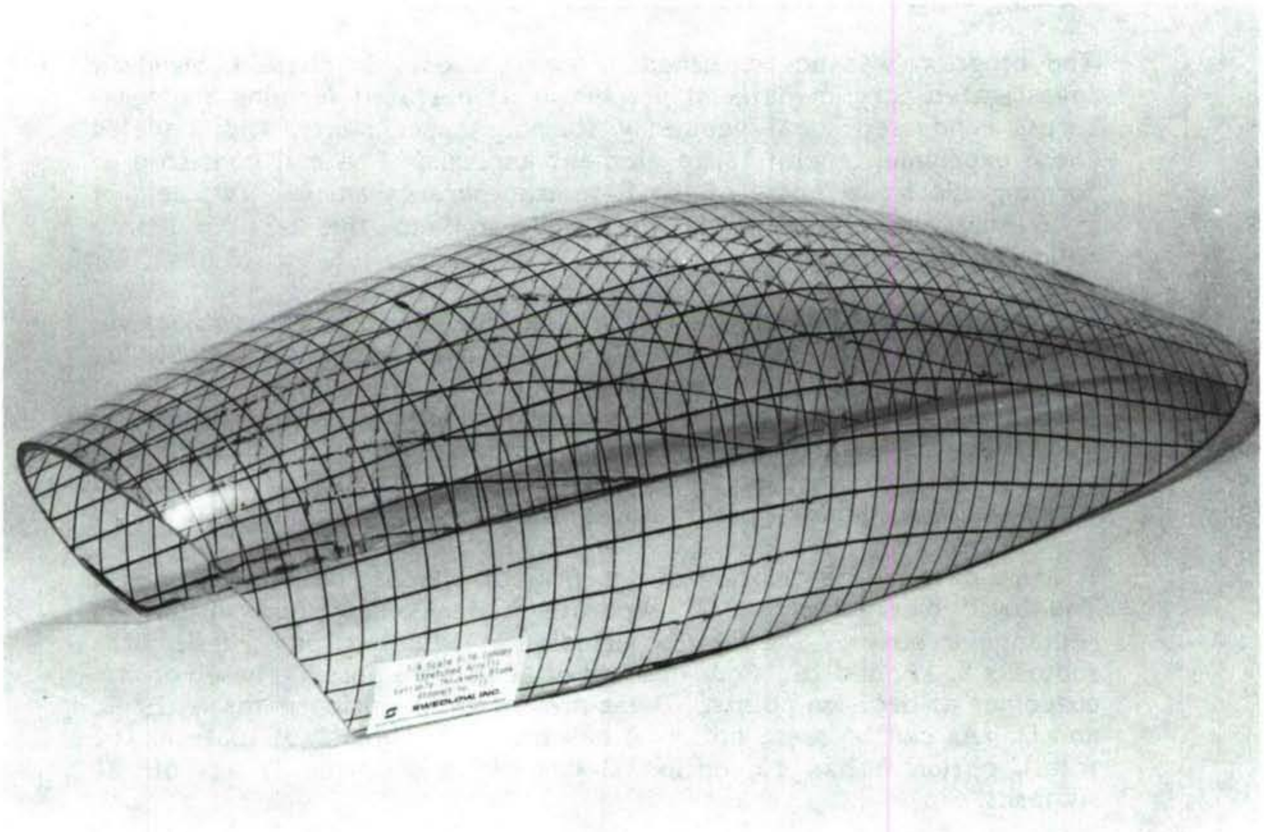


Figure 1. Stretched Acrylic 1/4 Scale F-16 Canopy Transparency of Virtually Uniform Thickness (Forming Attempt No. 11)

The results of this project verify an ability to manufacture uniform thickness compound curved shapes, such as that of the F-16 canopy. In addition, acrylic material properties (necessary for finite element stress analysis work) were generated at temperatures in the range of thermoforming. A finite element code (MARC) was identified and improvements were incorporated which show promise for stress-strain predictions involving very highly strained items. The objective of this project was clearly achieved.

SECTION II

PROGRAM OVERVIEW

The overall objective of this program was to demonstrate the concept of producing a uniform thickness canopy transparency through sub-scale forming experimentation and computer modeling.

The program was accomplished in two phases. In phase I, Swedlow investigated acrylic material properties at elevated forming temperatures, conducted ideal geometry forming experiments, and modeled these experiments with finite element analysis. Phase II consisted of forming 1/4 scale model of the F-16 transparency shape. Two sets of F-16 subscale canopy parts were delivered to the US Air Force following this effort.

The program was structured to efficiently arrive at the objective. Initially it was uncertain that all of the anticipated tasks could be executed successfully within the budget. For example, the ability of the finite element modeling to accurately predict experimental results was unknown. In addition, the computer modeling could be costly and prohibit further computer development. Questions such as these could only be answered during program execution.

A more detailed description of the project plan is shown in Figure 2. The logic diagram shows 21 separate subtasks described within the rectangular boxes. The yes/no circles are logical outputs of decision subtasks 8, 12, and 16. Four courses of action are possible based on the outcomes at decision points. These are shown as option paths A, B, C, and D. As can be seen, option A has the least number of subtasks (12 total), option B has 15, option C has 19, and option D has all 21 subtasks.

During the program execution, option path B was found appropriate. This course of action resulted from the need to reconfigure the finite element program. The computer modeling of the acrylic hemisphere (subtask 11) was the most advanced shape analyzed by the computer model. The uniform thickness canopy trials were based on experimental iteration instead of computer modeling predictions.

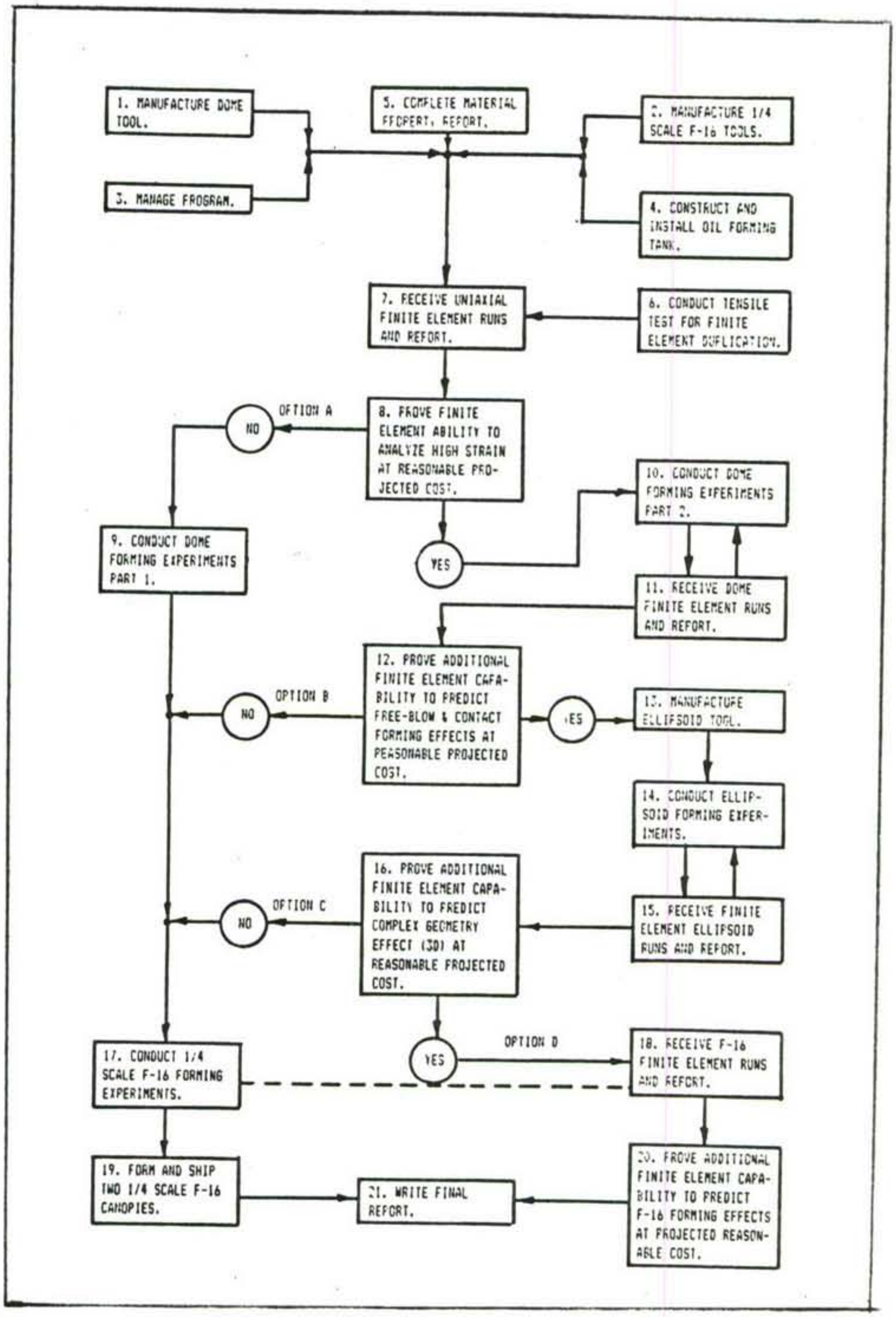


Figure 2. Program Logic Diagram

SECTION III

FINITE ELEMENT ANALYSIS INVESTIGATION

In order to understand the limits of various forming processes, it is advantageous to have a mathematical prediction technique. In the case of forming a uniform thickness F-16 forward canopy, the prediction method should be capable of determining the original material thickness profile.

The predictive tool chosen to perform this analysis was a computer finite element method. The finite element code would need to be capable of processing high material strains (greater than 200%) and material property non-linearities.

The use of the finite element model predictions could potentially avoid the high cost of experimentation associated with any new compound curved shape. The selected code execution must involve reasonable costs in order to offset the cost of an experimental approach. The total cost of performing each F-16 model run was chosen to be less than $3000. This was thought to be a reasonable trade-off limit based on the cost of experimentation and the iteration process of computer modeling.

The objectives of the finite element phase of the program were as follows:

a) Identify a code which, after possible modification, could handle thermoforming processes involving large strains (up to 200 percent).

b) Prove the capability of the code by a thorough analysis of progressively more difficult problems.

c) Estimate the computer costs of the true canopy modeling runs at each step of the code proof process.

d) Terminate the code development and future modeling runs if the technical accuracies or the cost of execution estimates are found unfavorable.

The finite element code which was selected to model the thermoforming process was MARC. MARC is a non-linear general purpose finite element code offered by MARC Analysis Research Corporation in Palo Alto, California. It was selected over other codes based on a number of factors:

a) MARC was one of a few finite element codes which offered a proven method to model rubber-like materials of strains exceeding 200 percent.

b) MARC offered the most comprehensive non-linear analysis capabilities and recently added a new viscoelastic capability [1].

c) Confidence expressed by Dr. Michael Burke of MARC Analysis and his proposal to do this work was very influential.

d) Recommendations of finite element experts not a part of MARC Analysis were positive.

The planned validation of the MARC code capability was based upon comparison of the model results to the experimental results. The models and experiments were planned to increase in complexity until a F-16 canopy was modeled with the computer code. The plan called for the modeling of four acrylic thermoforming experiments:

a) A uniaxially loaded tensile specimen

b) A hemisphere shape

c) An ellipsoidal dome shape

d) An F-16 canopy shape.

The first two experiments were to use MIL-P-8184 cast acrylic and the last two experiments were to use MIL-P-25690 stretched acrylic. The cast acrylic material was necessary for the tensile specimens in order to obtain true uniaxial stress-strain data.

Only the first two finite element models a) and b) above were performed within the time period of this contract. Models c) and d) were not performed because of time constraints.

The tensile specimen was successfully modeled using constant strain rate material properties. The finite element model duplicated the experimentally generated results for engineering strains up to 200%.

Prior to modeling of the hemisphere forming experiment, it was decided to modify the MARC code. The modification would incorporate a rubber-like shell element which would be less expensive to use than the existing more complex rubber-like brick elements. Upon completion of this task, MARC modeled the hemisphere forming experiment. The shape predictions were quite accurate, but the thickness and strain profiles were inaccurate. These results indicated that some additional material property modifications were required. A further discussion of the tensile specimen and hemisphere models is given later in this section.

The general characteristics of the MARC code which were tested include:

a) A Mooney strain energy material characterization.

b) A 2-D axisymmetric rubber-like shell element with large strain and large rotational response capability.

c) An instantaneous stress-strain computation for a plane stress condition.

d) A gap element interface between contact surfaces.

The results of this analysis work are encouraging. The technical feasibility of accurately modeling a canopy forming process is still probable. Code execution costs, while not demonstrated sufficiently, do not appear to be prohibitive.

MARC Analysis of Acrylic Tensile Specimens

The objective of modeling the acrylic tensile specimen was to demonstrate the ability of the MARC finite element code to simulate experimental results. The general intent was for MARC to provide an initial demonstration of its capability to analyze large strains (up to 200 percent) and the non-linear response of acrylic. The constitutive equations derived from the tensile tests were used in the hemisphere forming model.

The tensile tests were performed at a constant strain rate and a uniform temperature. At forming temperatures above the glass transition temperature, the acrylic is incompressible (i.e., Poisson's ratio = 0.5). Over large strain ranges, the acrylic behaves in a non-linear elastic manner.

An analysis procedure exists with the MARC code for the large deformation response of non-linear elastic and incompressible structures. This is the "Mooney" formulation. For the tensile model, the Mooney formulation was used and the capability was restricted to isotropic behavior.

The Mooney formulation requires that the constitutive law be described in terms of a strain energy potential (W) which is a function of the strain tensor. The strain energy function can be defined in terms of the three invariants of the strain tensor:

$$W = W(I_1, I_2, I_3) \tag{1}$$

The strain invariants (I), expressed in terms of the extension ratios (λ), are

$$I_1 = \lambda_1{}^2 + \lambda_2{}^2 + \lambda_3{}^2 \tag{2}$$

$$I_2 = (\lambda_1 \lambda_2)^2 + (\lambda_2 \lambda_3)^2 + (\lambda_3 \lambda_1)^2 \tag{3}$$

$$I_3 = (\lambda_1 \lambda_2 \lambda_3)^2 \text{ ; } I_3 = 1 \text{ for incompressible deformation.} \tag{4}$$

where

λ_n = instantaneous length/original length, n = 1, 2 or 3.

The particular functional form of the strain energy function in the MARC code is

$$W(I_1,I_2) = C_{10}(I_1-3) + C_{01}(I_2-3) + C_{11}(I_1-3)(I_2-3) + C_{20}(I_1-3)^2 + C_{30}(I_1-3)^3 \quad (5)$$

The user has the option to include some or all of the terms. For small to intermediate strains the first two terms are sufficient and this expression is commonly referred as the "Mooney-Rivlan" form. This was not a sufficient description for this problem. The full available expresion was required for the tensile test modeling.

A stand alone computer program was generated in order to develop the five material constants required by the strain energy function. The strain energy function is transformed into a true stress-true strain relationship involving the five constants. Points selected from true stress-true strain test data are used in this determination.

It is further required, however, that the constitutive form be checked for stability at all regions within the strain space. This stability requirement is a mathematical artifice and requires that the following determinant be satisfied:

$$\frac{\partial^2 W}{\partial \varepsilon_i \, \partial \varepsilon_j} > 0 \quad (6)$$

A stand alone computer program was generated which can be used to verify stability over a broad range of principal extension ratios. If necessary, the strain energy function coefficients are modified until stability is achieved.

Two finite element models were used to analyze the tensile specimens. One was a two-dimensional plane strain element. The second was a three-dimensional element. Both models made use of the so-called "Herrmann elements", which are second order isoparametric elements having hydrostatic pressure variables at the corner nodes which enforce the constraint of incompressibility.

Both of these models closely simulated test results. The test results and the result of generalized plane strain model are compared in Figures 3 and 4. The experimental tests resulted in approximately a 16% variability in stress ((2000-1700)/1850 at 1.2 in/in) and a 20% variability in thickness reduction ((0.22-0.18)/0.20 at 100 lbs.). The MARC finite element results fell between these two experimental results.

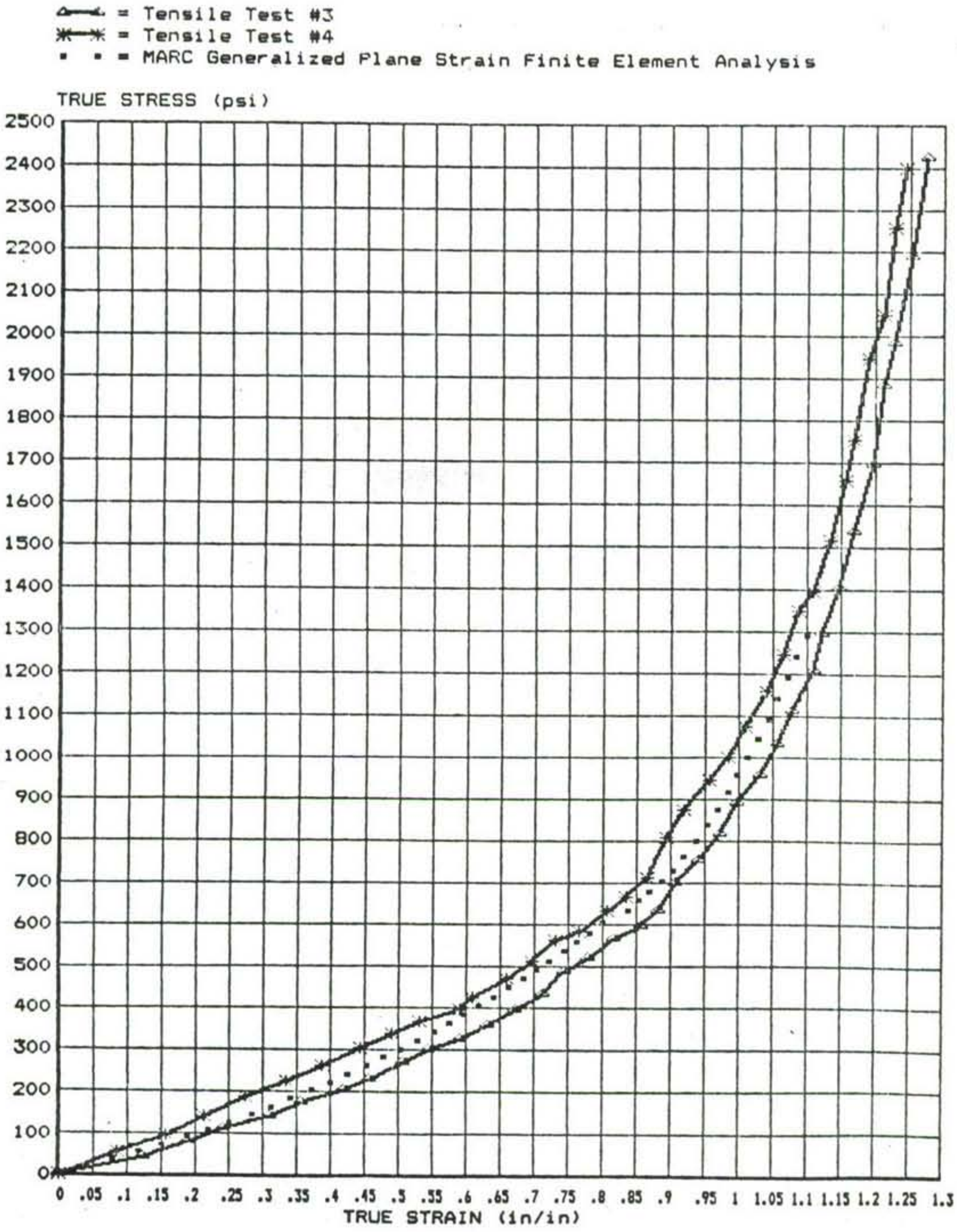


Figure 3. MIL-P-8184 Tensile Test Numerical/Experimental Comparison: True Stress vs True Strain Curves

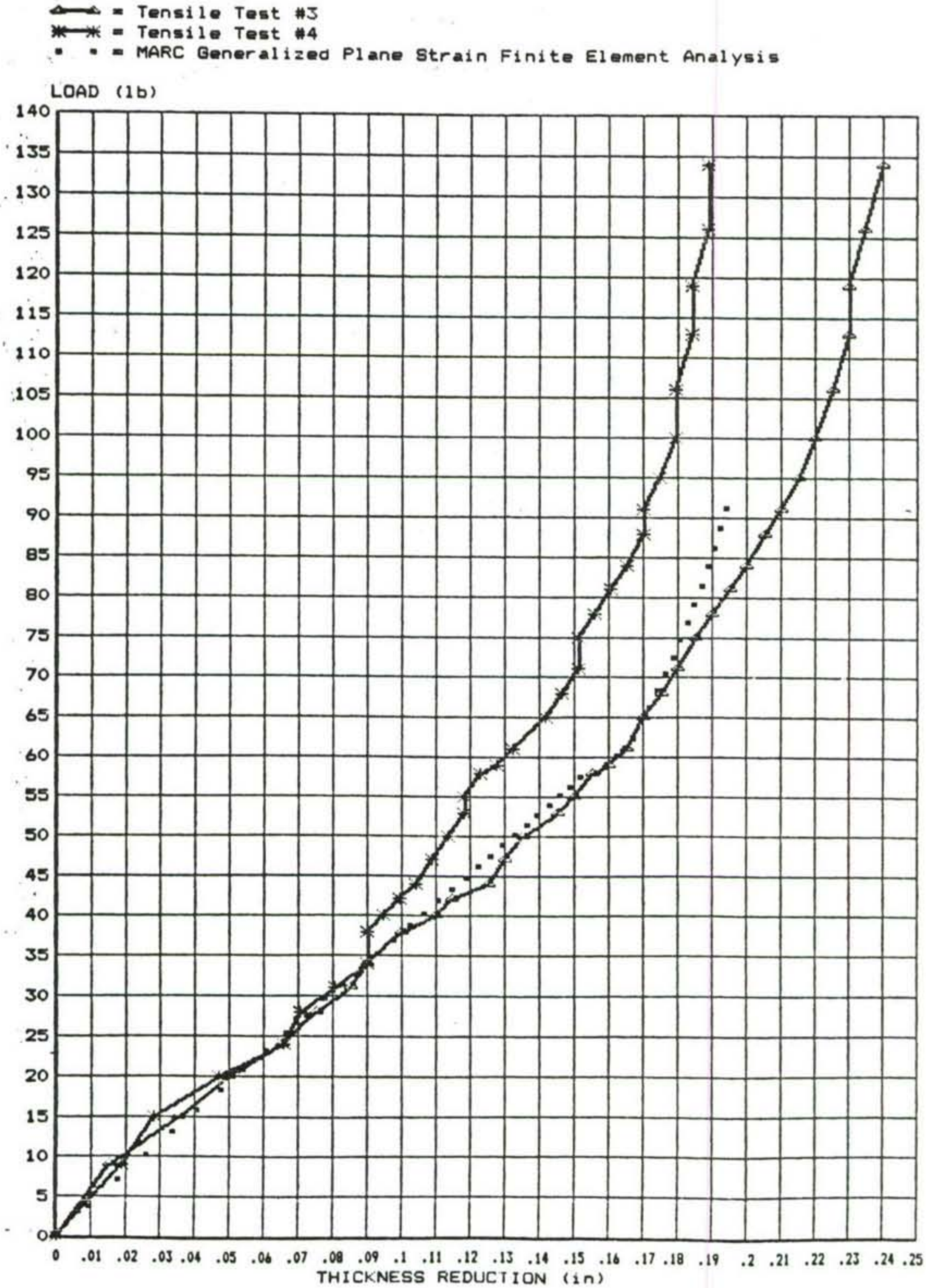


Figure 4. MIL-P-8184 Tensile Test Numerical/Experimental Comparison: Load vs Lateral Thickness Reduction

MARC Analysis of Acrylic Hemisphere

The objective of the hemisphere model was to demonstrate the ability of the MARC finite element analysis code to simulate the experimental results of thermoforming an acrylic hemisphere. Stresses, strains, general geometry, and spatially non-uniform thicknesses were to be determined analytically and compared to experimental results.

The general constitutive relationship developed in prior tensile test modeling was used. Thus, a constant strain rate was assumed. It was necessary, however, to modify this relationship in order to handle the simple plane stress condition which prevails for shell like structures.

An existing two node, axisymetric, thin shell element was modified in order to handle large strains and curvature components of strain. This new element was checked by analyzing a case in which a relatively simple closed form solution existed and was found to be acceptable.

Gap elements were employed in the restraint region of the disk which was thermoformed into the hemispherical shape. A subroutine was written to define the gap orientation and closure distance which is used in conjunction with the gap element. A number of MARC code subroutines were also modified in order to account for the new element, the constitutive formulation, and the curvature components of strain.

Hemispheres were formed at 10 psi inflation pressure (see Figure 5 and 6). It was found that 15 psi was required in the analysis in order to develop a profile comparable to experimental results. The profile match was nearly exact. The predicted crown thickness of 0.115 inch was 48 percent thicker than the actual thickness of 0.072 inch. See Figures 7 through 11 for comparisons between experimental and numerical results. The comparisons are given in terms of engineering strain versus a profile ratio. Although the experimental and numerical curves did not match, the general shape of the stress and strain gradients were found to be quite satisfactory.

These modeling inaccuracies also exist in tensile test specimens. A portion of the problem is due to the approximate 20% variation in tensile test data. It was also determined that the model did not correctly simulate forming in the gripped area. In the experiment, this material was not allowed to stretch at all. According to the finite element model, the thickness of the ring area decreased to 0.182 inch where in reality it remained at 0.250 inch. The finite element model therefore allowed the acrylic in the gripped area to migrate into the hemisphere, effectively reducing the values of the hoop and radial extension ratio and lessening the effective thickness. This oversight can be relatively easily corrected for future runs.

Differences between the model and experimental results can also be explained in part by the fact that the model did not account for the

time-dependent effects of the acrylic. In the experiments, for any given dome cross-section, the strain rates varied from the crown (highest strain rate) to the circular gripped area (no straining). In the model, however, all elements were considered to have identical strain rates. Since acrylic is very sensitive to strain rates, if these time-dependent effects were properly modeled the computer results should be much more accurate. This would require more material property equations which would be based upon tensile creep or relaxation test data. The MARC code already is configured to accept these time-dependent effects and additional code modifications would therefore not be necessary.

More work needs to be done to resolve the discrepancies between numerical and experimental results. Generally, however, the analysis technique looks promising. Run-time information is still insufficient to adequately predict the cost of performing a full canopy model run.

The two-node axisymmetric shell element is a precursor to the 4-node shell element necessary for the more complex canopy geometries. Modifications to this 4-node shell element to become a viscoelastic or rubber-shell element will be required and will be similar to the modifications of the two-node shell elements. This process is straightforward and should be relatively easy to perform.

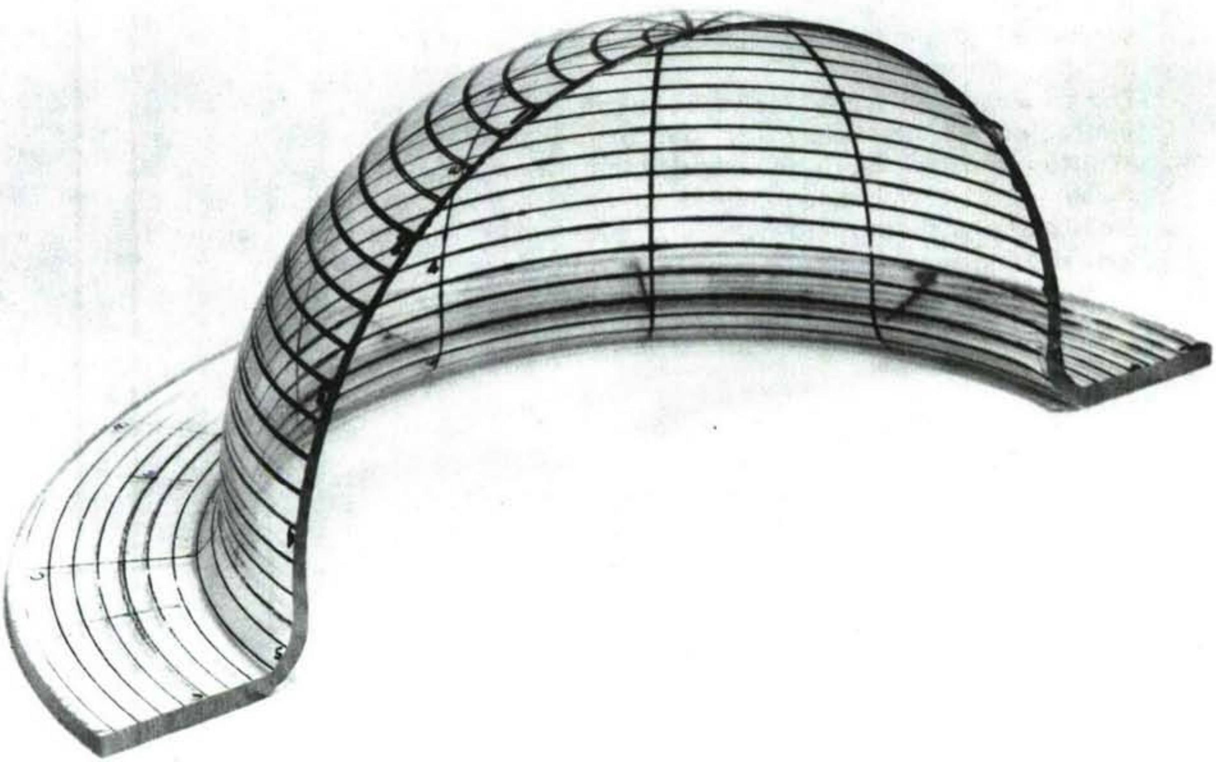
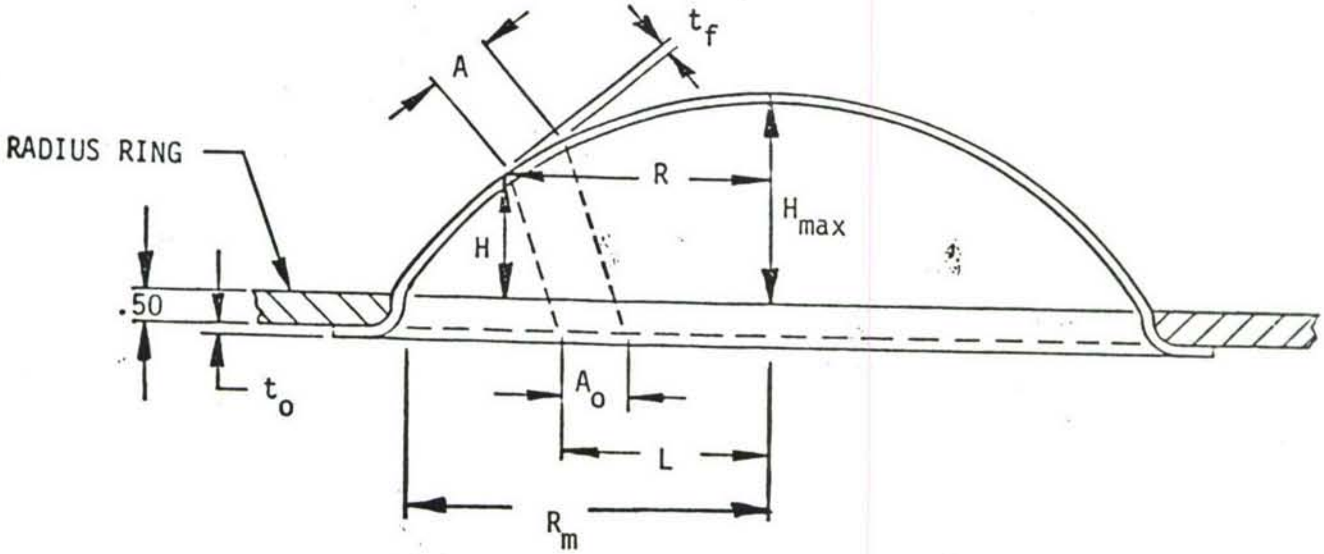


Figure 5. MIL-P-8184 Free-Blown Hemisphere



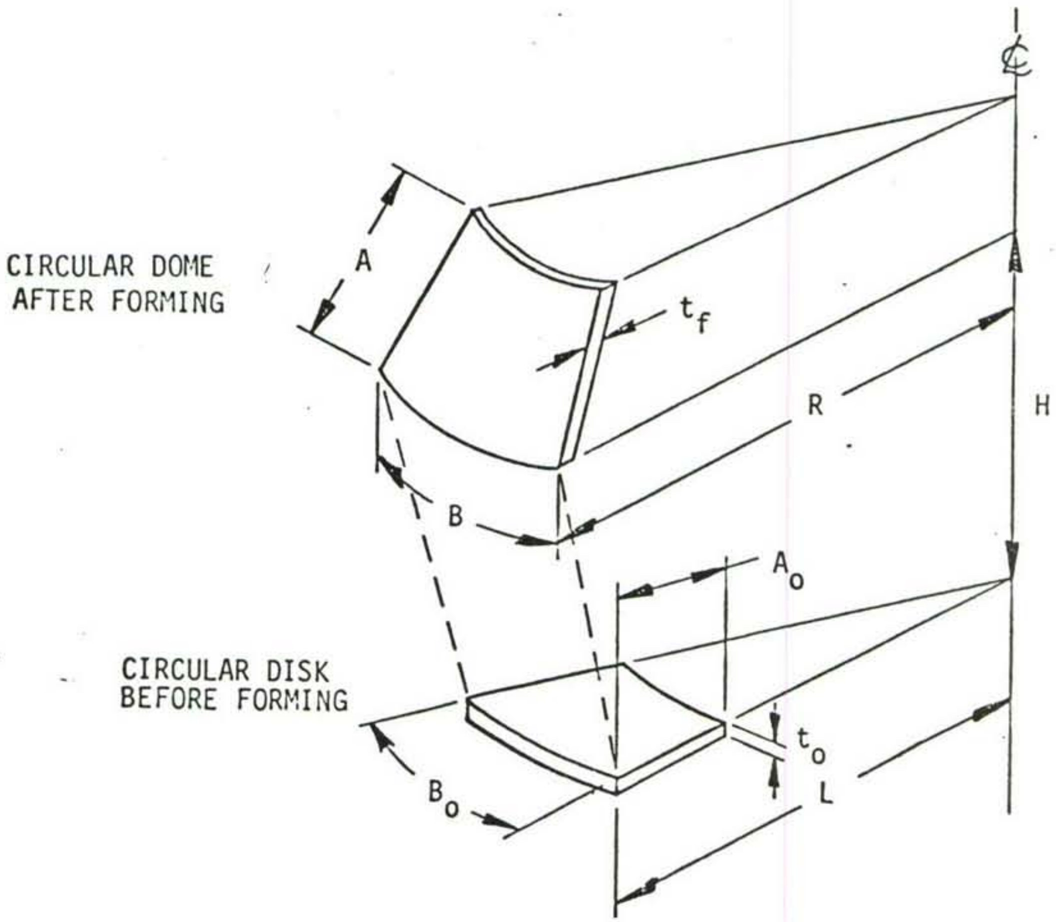


Figure 6. Description of Measurements for Circular Disk and Hemisphere

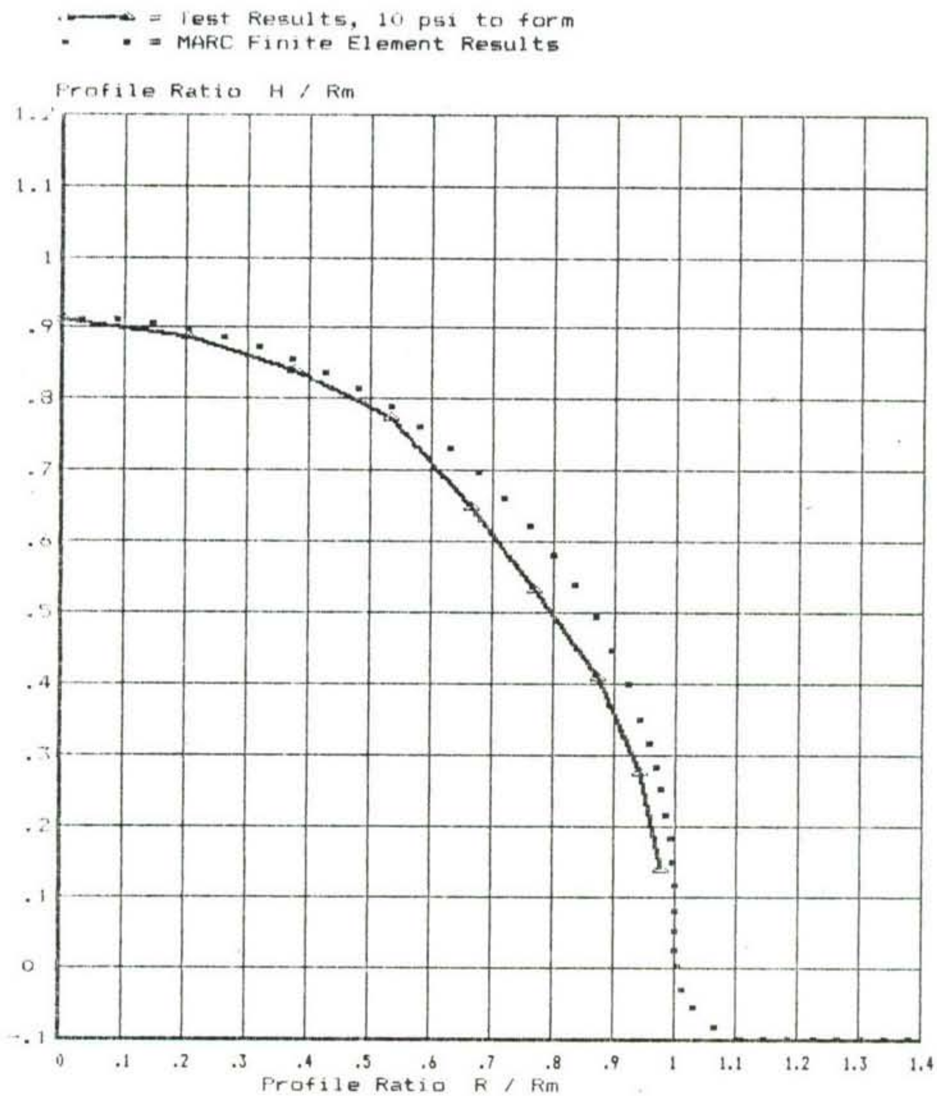


Figure 7. MIL-P-8184 Hemisphere Numerical/Experimental Comparison: Normalized Deformed Shape vs Radius

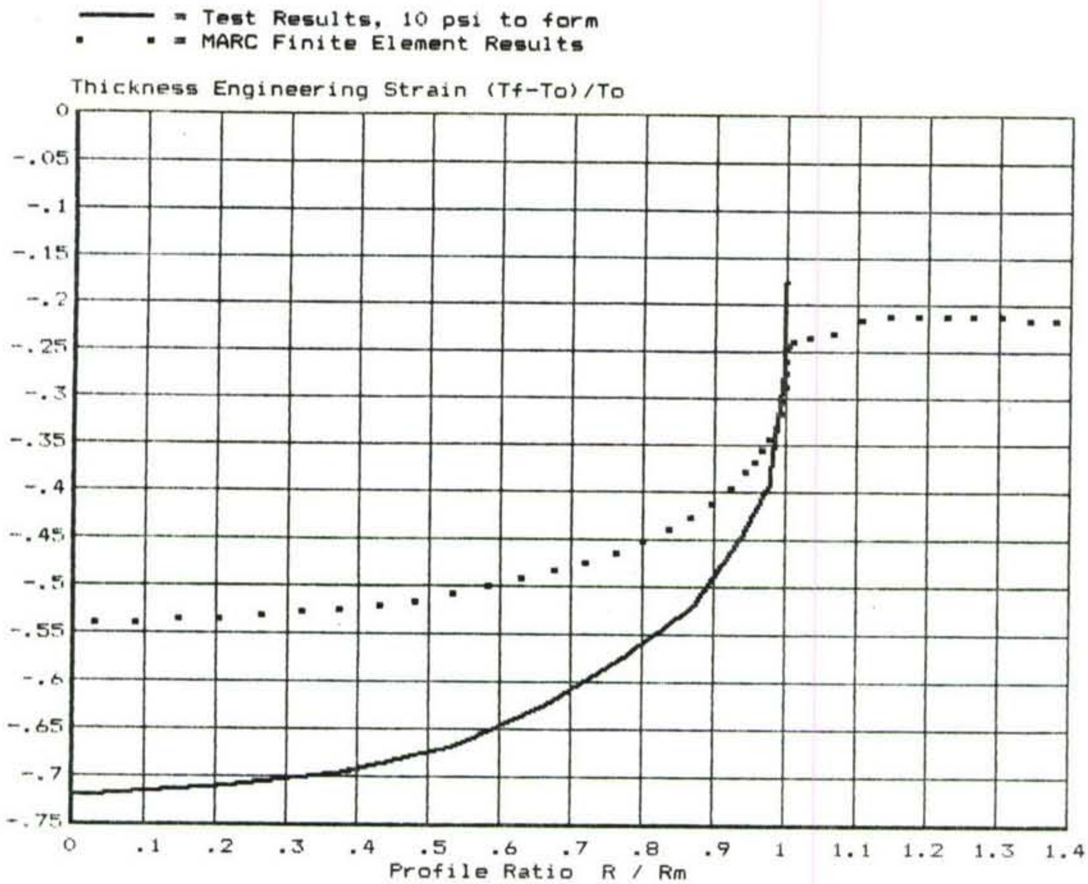


Figure 8. MIL-P-8184 Hemisphere Numerical/Experimental Comparison: Thickness Engineering Strain vs Radius

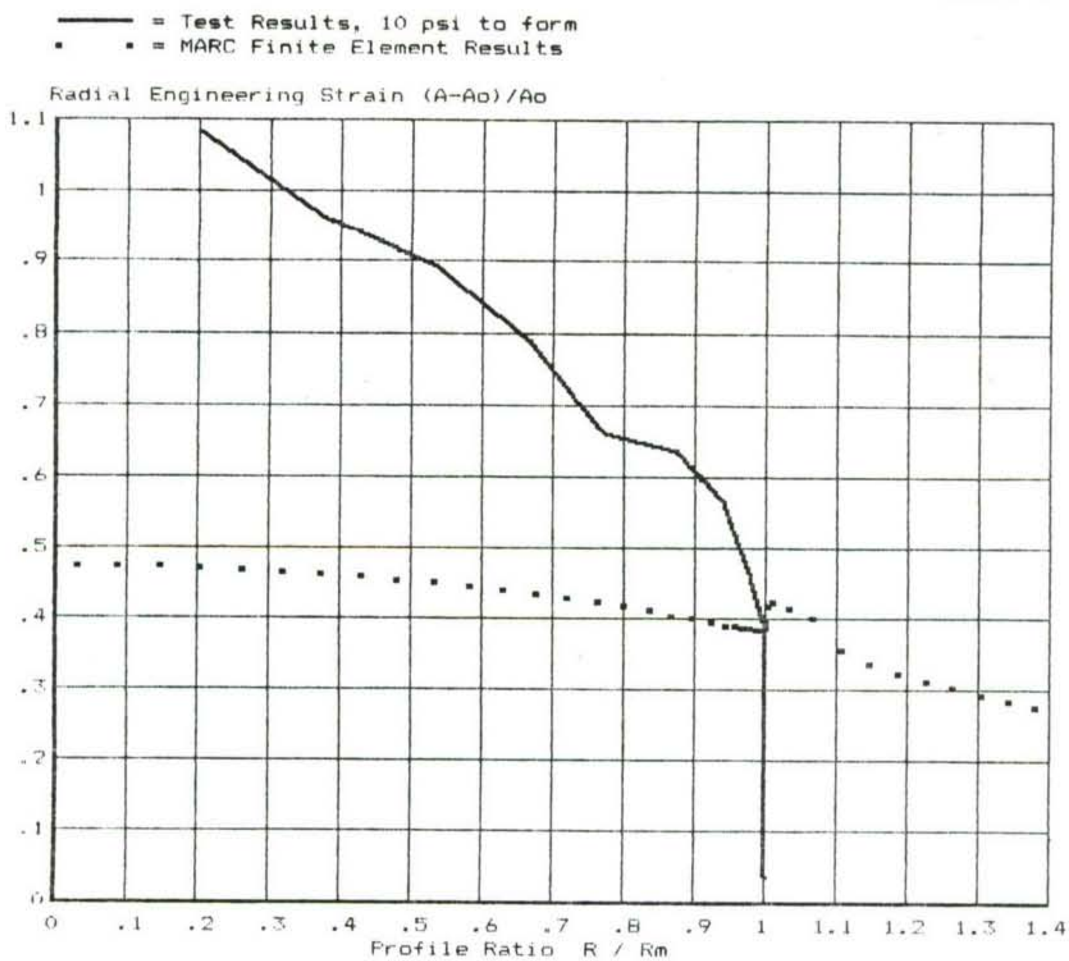


Figure 9. MIL-P-8184 Hemisphere Numerical/Experimental Comparison: Radial Engineering Strain vs Radius

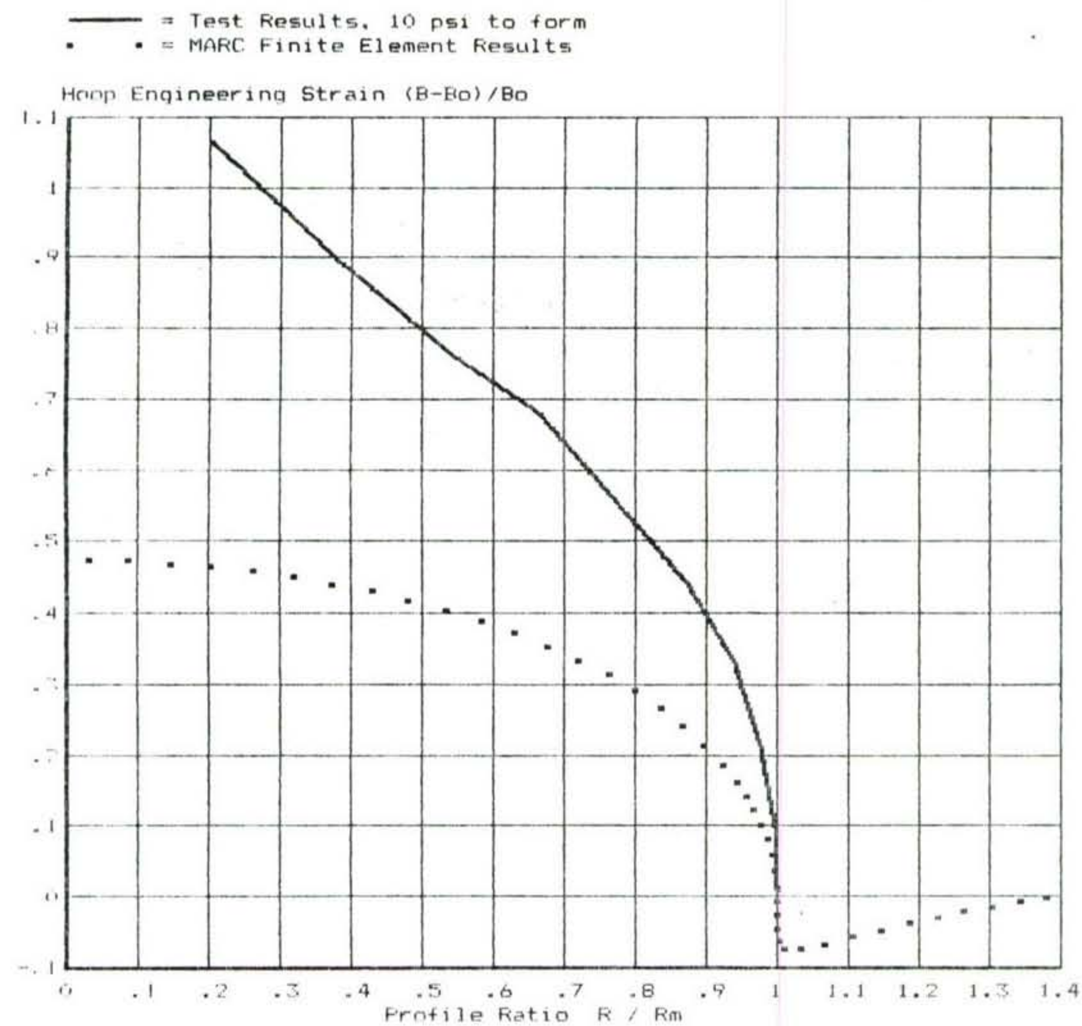


Figure 10. MIL-P-8184 Hemisphere Numerical/Experimental Comparison: Hoop Engineering Strain vs Radius

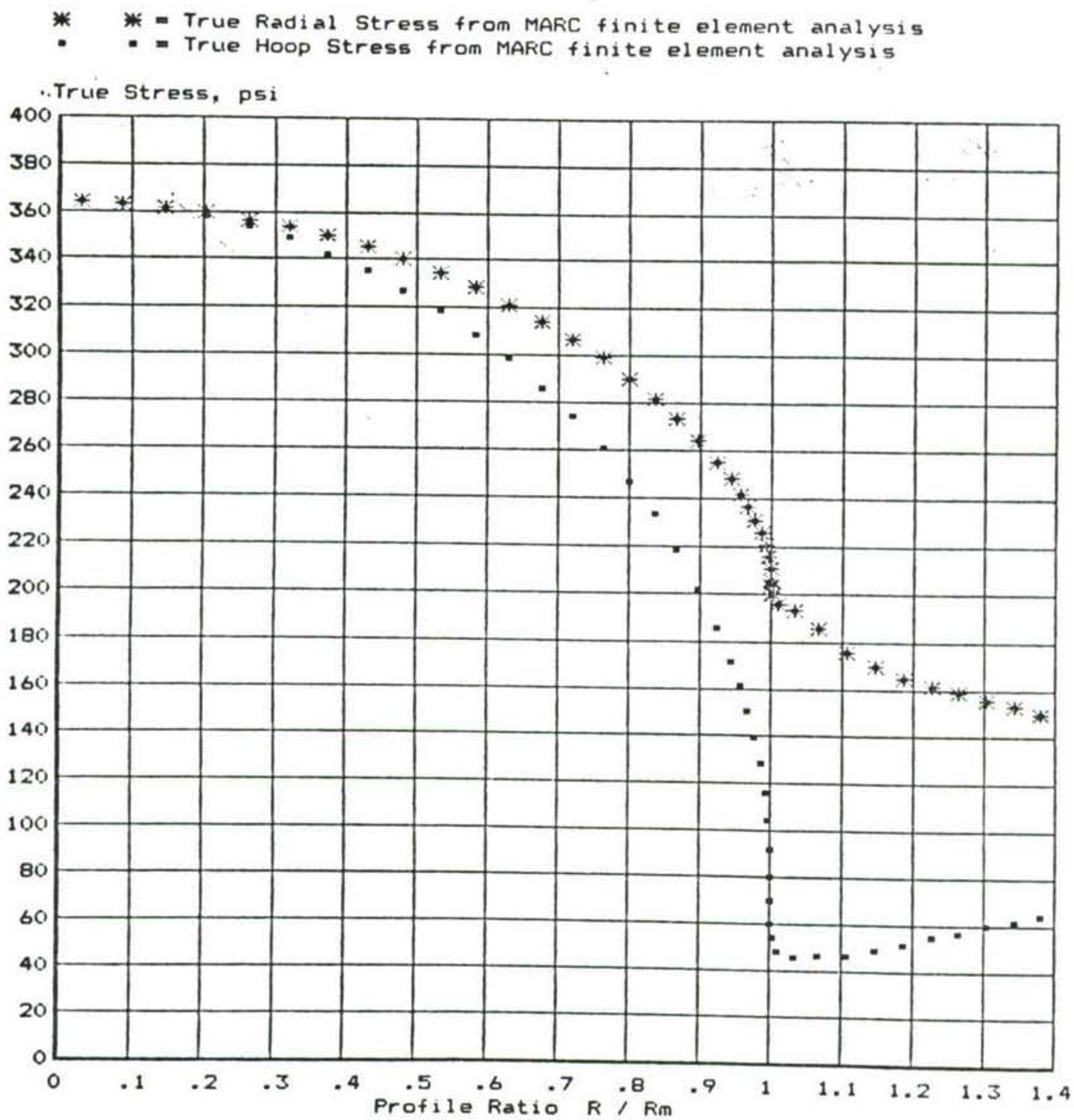


Figure 11. MIL-P-8184 Hemisphere Final Stress State

SECTION IV

ACRYLIC MATERIAL PROPERTIES AT THERMOFORMING TEMPERATURES

Prediction of thermoforming characteristics using a finite element stress analysis code requires an understanding of material properties at thermoforming temperatures. Thermoforming is generally done at material temperatures which are well above the glass transition temperature. Physical properties of plastic materials used in aircraft transparencies (specifically acrylic and polycarbonate) are poorly characterized at these temperatures.

The objective was to begin to develop the uniaxial tensile stress-strain characteristics of acrylic at temperatures in the range of 230°F to 350°F. As Cast MIL-P-8184 acrylic was used instead of stretched acrylic in order to derive true uniaxial material properties.

In general, the tensile properties of a material at a constant temperature (isothermal) may be described as a surface in the stress-strain-time domain as depicted below.[2]

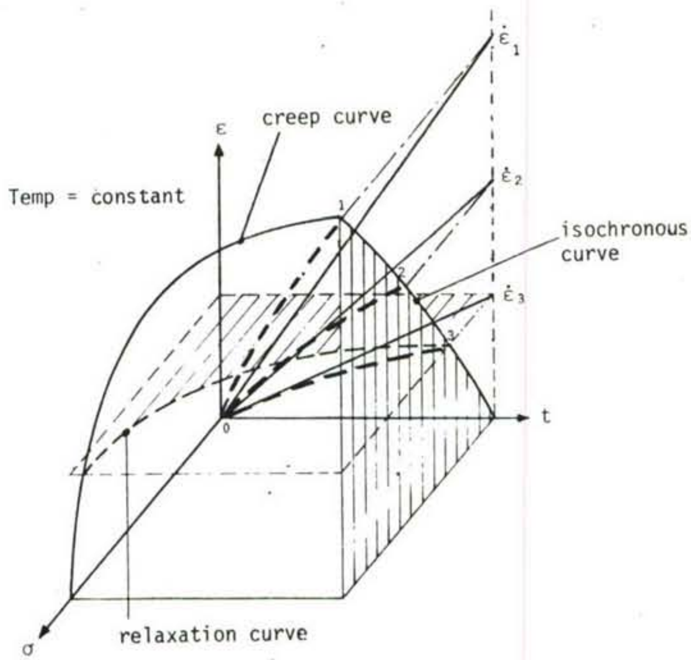


Figure 12. Stress-Strain-Time Domain

Tests were conducted at three strain rates (approximately 0.05, 0.20 and 1.00 in/in-min.) and at five temperatures (250, 260, 275, 300, 350°F). A constant strain rate was used. Ninety tests were performed. Sixty-three tests were used in the properties data base generated.

A test technique was developed for the tensile specimens which provided a cooled gripping area while maintaining an elevated temperature test section. A photographic method was used to provide measurement of the high strains.

The three dashed curves in Figure 12 (lines 01, 02 and 03) represent lines on the surface which are based on constant strain rate testing at three different rates. Curves such as these were generated by this test work. From this data it is possible to provide a limited estimate (only three data points) of the isochronous, creep, and relaxation curves. Reduction of the available data necessary to present these curves has not been completed because of an insufficient data base.

Ignoring the differences in properties associated with different strain rates, a few of the general tensile properties are shown in Figures 13-16. A few conclusions can be made from these graphs.

1) The initial tensile modulus drops by about 2 1/2 orders of magnitude as the temperature increases from the glass transition temperature (235°F) to 300°F. The rates of change of the tensile modulus on either side of this transition region are much less.

2) The ultimate tensile strain (strain at breakage) appears to plateau in the 250-300°F temperature region and above this temperature the strain allowable appears to decrease.

3) Maximum tensile strain appears to occur at about 260 - 275°F and is on the order of 200% (minimum). The maximum mean strain allowable measured was just over 300% but variation was large.

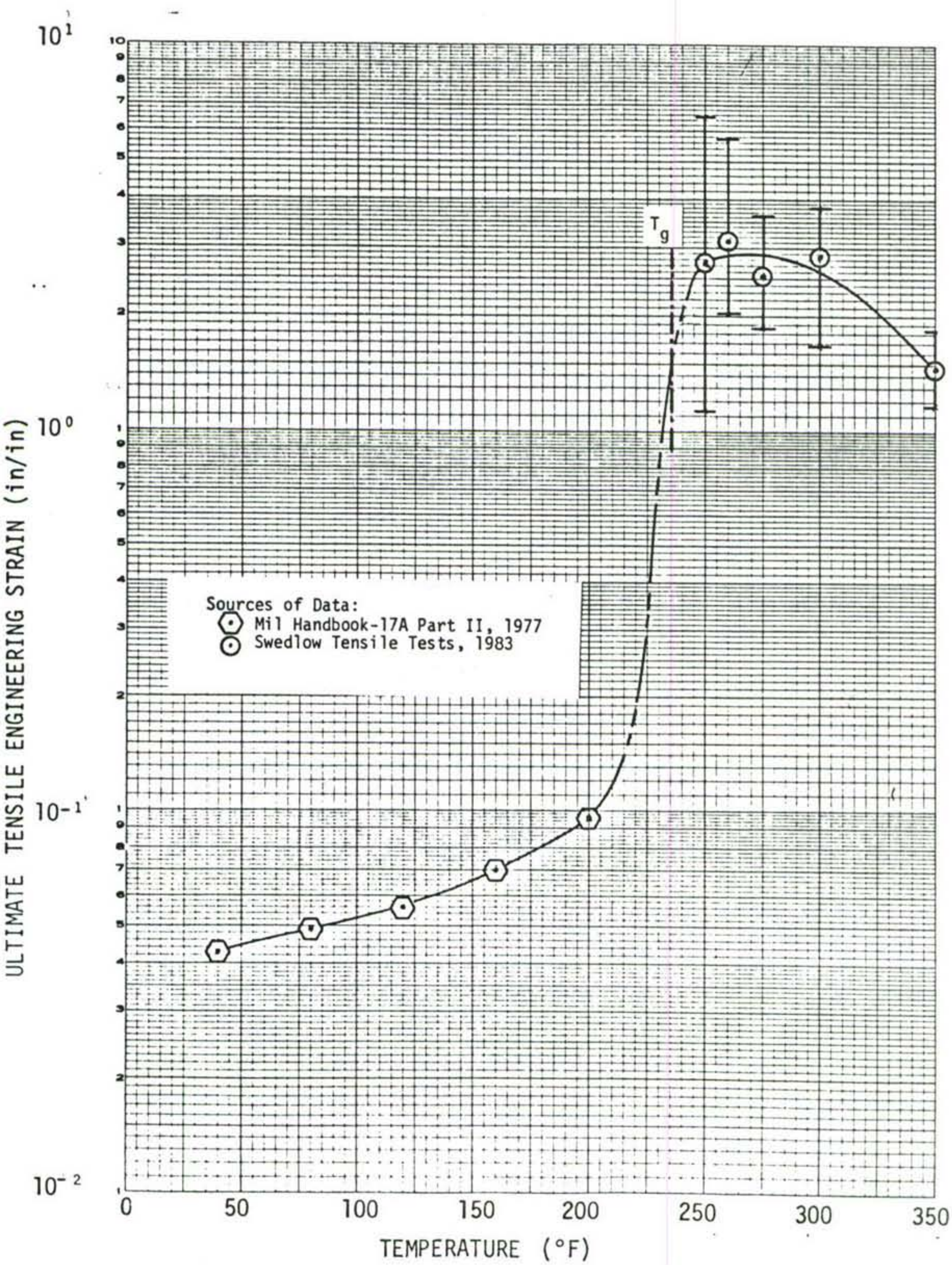


Figure 13. Ultimate Tensile Strain vs Temperature, MIL-P-8184

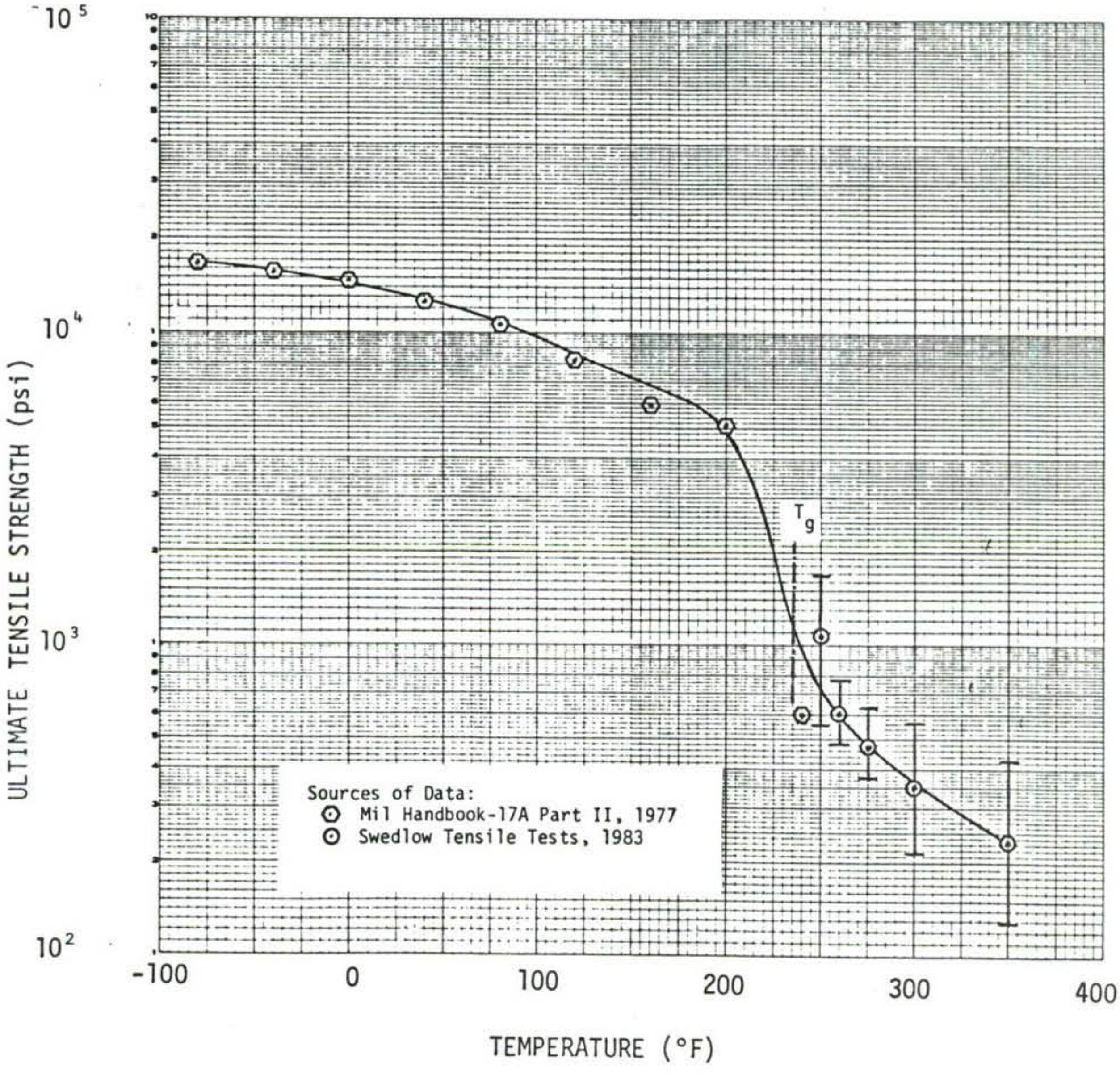


Figure 14. Ultimate Tensile Stress vs Temperature, MIL-P-8184

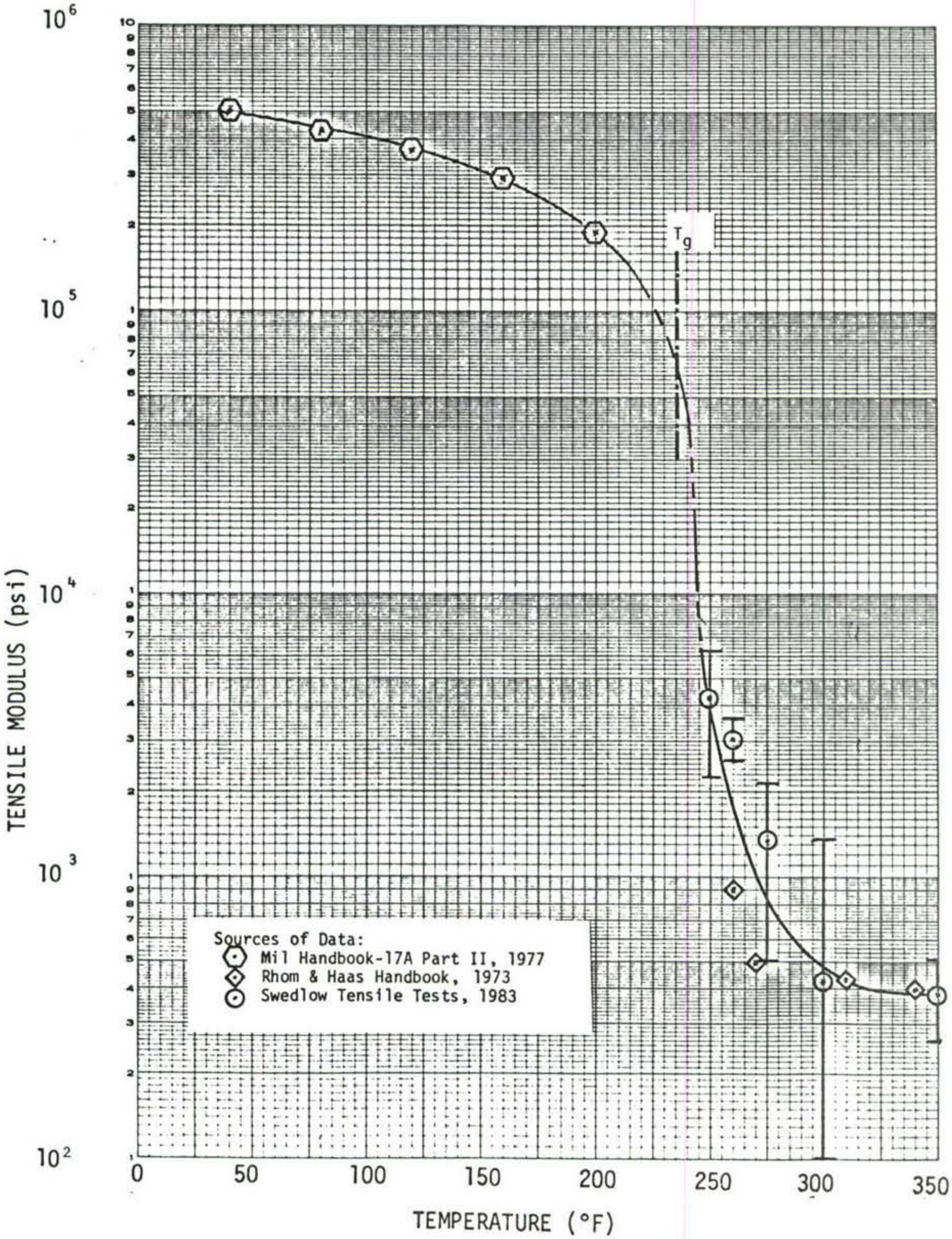


Figure 15. Tensile Modulus vs Temperature, MIL-P-8184

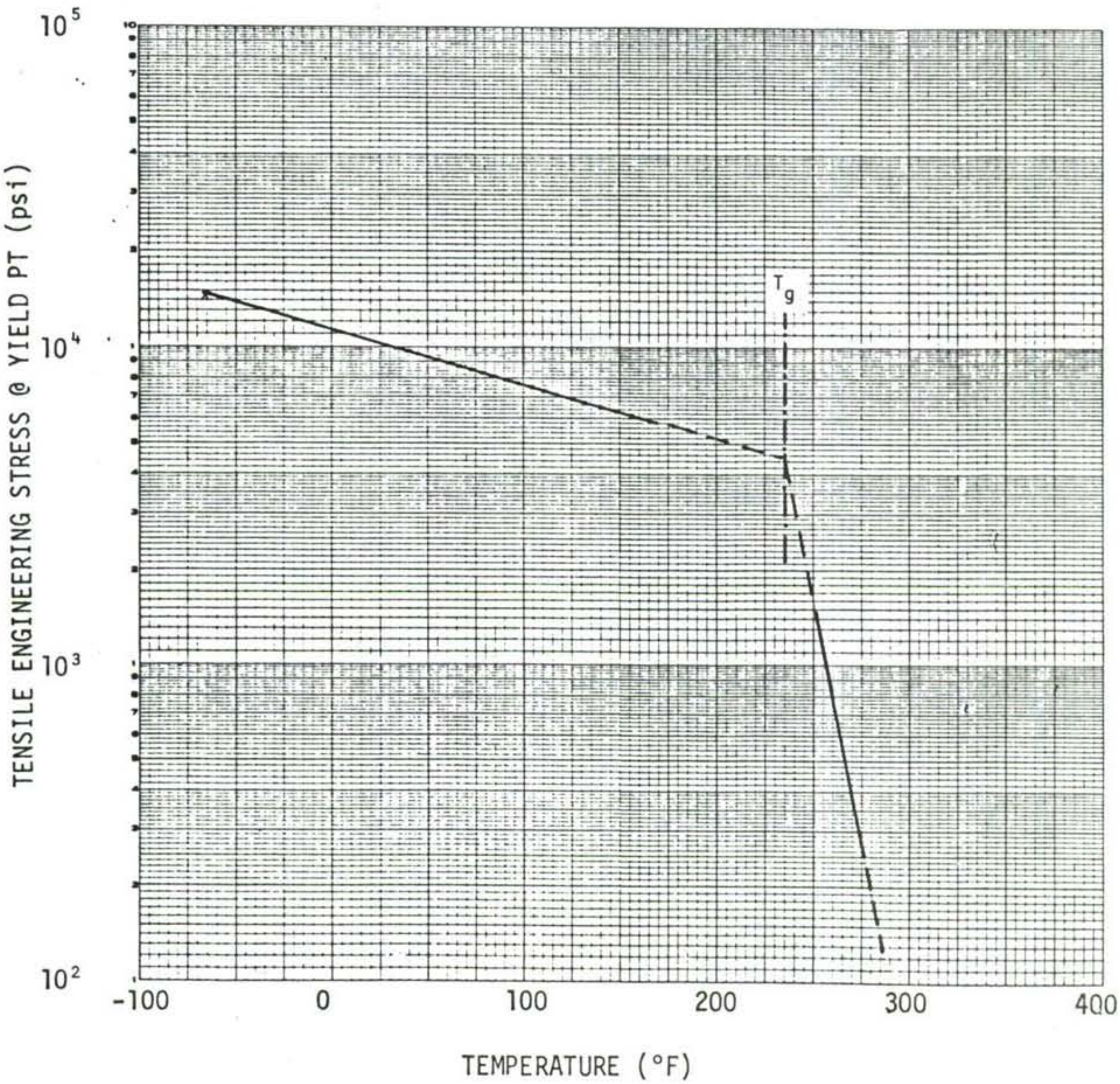


Figure 16. Approximate Tensile Stress
At Yield Point vs Temperature MIL-P-8184

At the strain rate of 0.20 in/in-min. the average engineering stress versus engineering strain is shown in Figure 17.

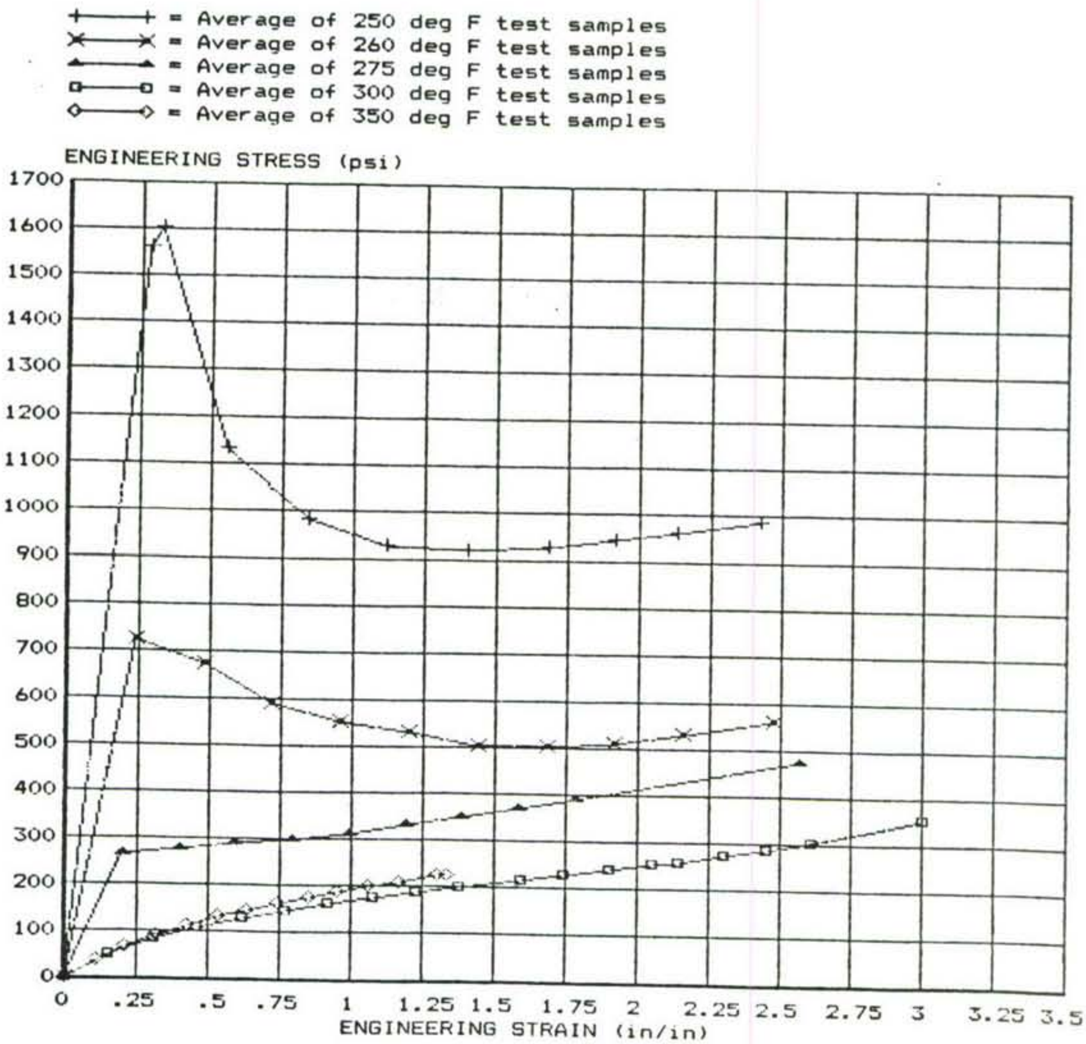


Figure 17. Average Engineering Stress vs Engineering Strain, MIL-P-8184

The effect of strain rate at 250°F is depicted in Figure 18.

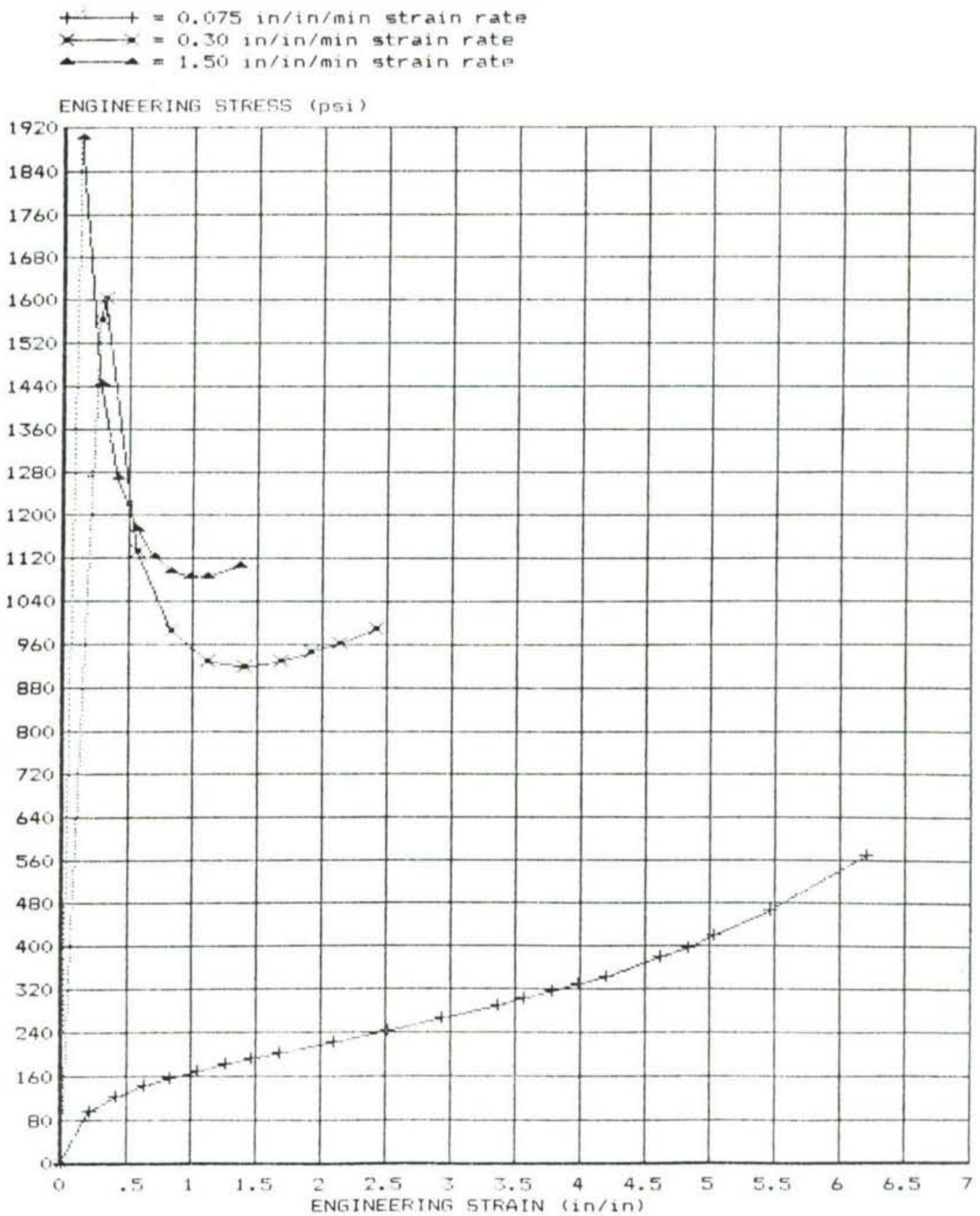


Figure 18. MIL-P-8184 Engineering Stress vs Engineering Strain, 250°F

The time dependent effects are particularly evident at the slow strain rate ($\varepsilon = .075$) at temperatures around 250°F.

The effect of strain rate is minimal at 300°F over the range of strain examined (see Figure 19 below). Nearly identical curves are found at 350°F.

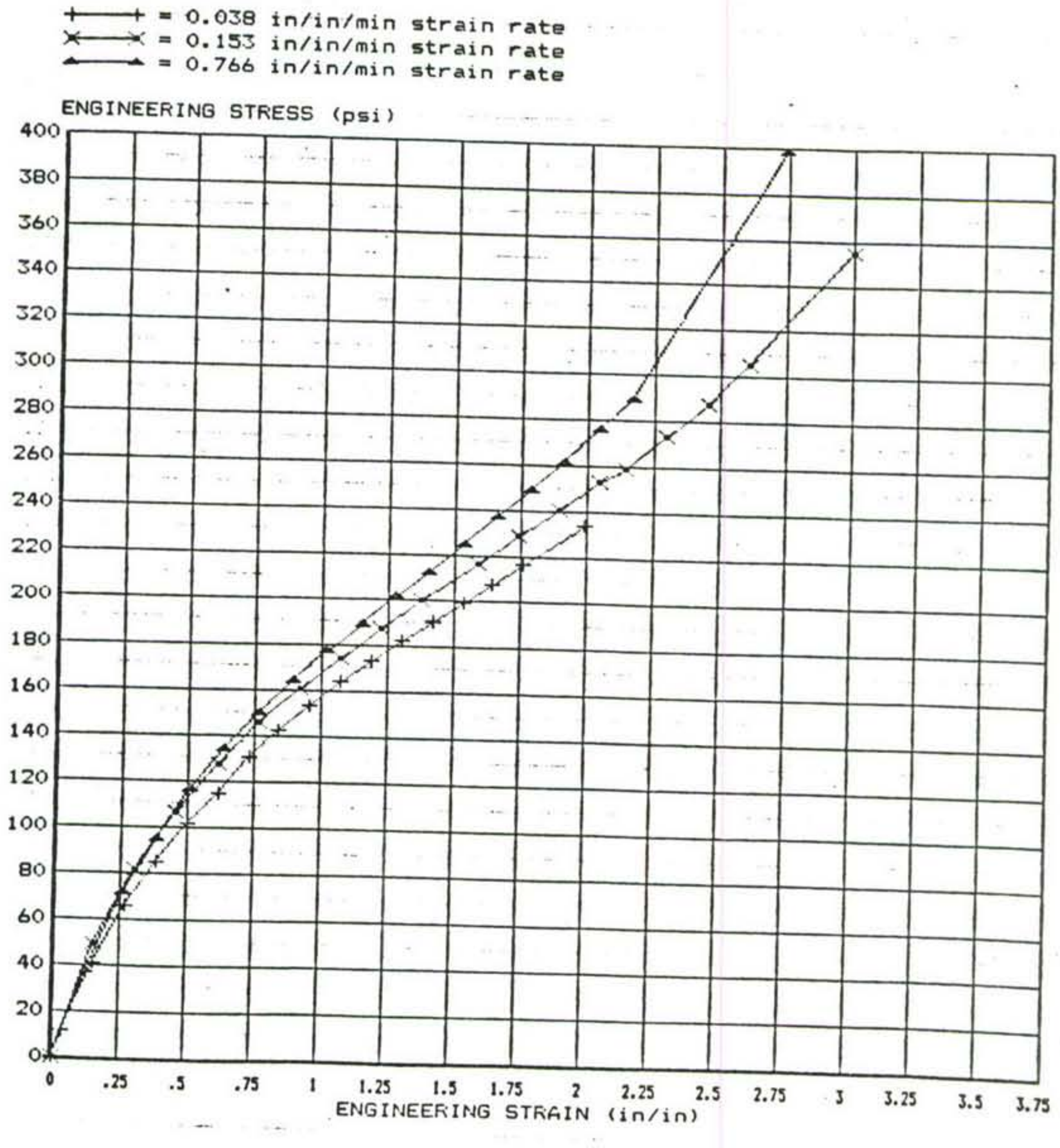


Figure 19. MIL-P-8184 Engineering Stress vs Engineering Strain, 300°F

Although additional material characterization work is required in this high temperature regime, sufficient data has been generated to proceed with finite element analysis of the thermoforming process. A basic test method has been established which is able to contend with the problems of high temperature testing of plastic materials. Data on acrylic tensile properties above the glass transition temperature has been greatly expanded by this work.

SECTION V

SUB-SCALE F-16 CANOPY FORMING EXPERIMENTATION

The concept for developing a uniform thickness for a compound contoured canopy is based on the use of a non-uniform thickness sheet stock. This is in contrast to the possibility of subsequently grinding to a uniform thickness, an otherwise non-uniform canopy.

In the absence of an analytical predictive technique, it is possible to arrive at the required sheet stock contour through a trial and error experimental process. The objective was to form stretched acrylic sub-scale F-16 canopies which would have a final uniform thickness (i.e., thickness variation less than 15%). The method for achieving this objective should be based on the use of a non-uniform thickness sheet stock.

The experimental plan was based on the following steps:

1) Form a uniform thickness sheet to the canopy shape and measure the resultant thickness profiles.

2) Prepare a new non-uniform thickness sheet wherein the thickness variations are based on the difference between the starting and final thicknesses found in step (1).

3) Form the non-uniform thickness sheet to the canopy shape and measure the resultant thickness profiles.

4) Adjust the non-uniform sheet thickness based on the variation from uniformity which are found.

A 1/4 scale F-16 canopy form die was manufactured in order to perform this experimentation. Sheet stock thickness profiling was accomplished in a laboratory manner. Eleven forming trials were attempted. Seven of these resulted in acceptable canopy shapes.

Thickness profiles of the F-16 canopy resulting from the forming of a uniform thickness sheet are shown in Figure 20. Results of an intermediate trial are shown in Figure 21. The final trial (attempt 11) yielding the best uniformity is depicted in Figure 1. The flat blank contour of this part prior to forming is shown in Figure 22. Figure 23 illustrates the final thickness profile of this canopy after forming was performed. Only a very small region in the aft end of the canopy exceeds the 15% maximum thickness variation criteria. Correction of this small discrepancy could be easily corrected on any subsequent forming attempt.

It is anticipated that this iterative procedure, when employed for any new shape, could yield an acceptable starting sheet thickness profile in three to five forming attempts.

Two sub-scale F-16 canopies were submitted to the Air Force Wright Aeronautical Laboratories (see Figure 24). One of these is highly thinned based on the use of a uniform thickness sheet stock. The other is a uniform thickness canopy resulting from the thermoforming of a non-uniform thickness sheet. These parts illustrate the degree of thickness correction which may be obtained by this process and confirms the feasibility of the method.

It is possible to develop full-scale tools, based upon this work, which will produce uniform thickness acrylic F-16 canopies. Practical full-scale manufacturing methods are envisioned for making non-uniform thickness flat sheets.

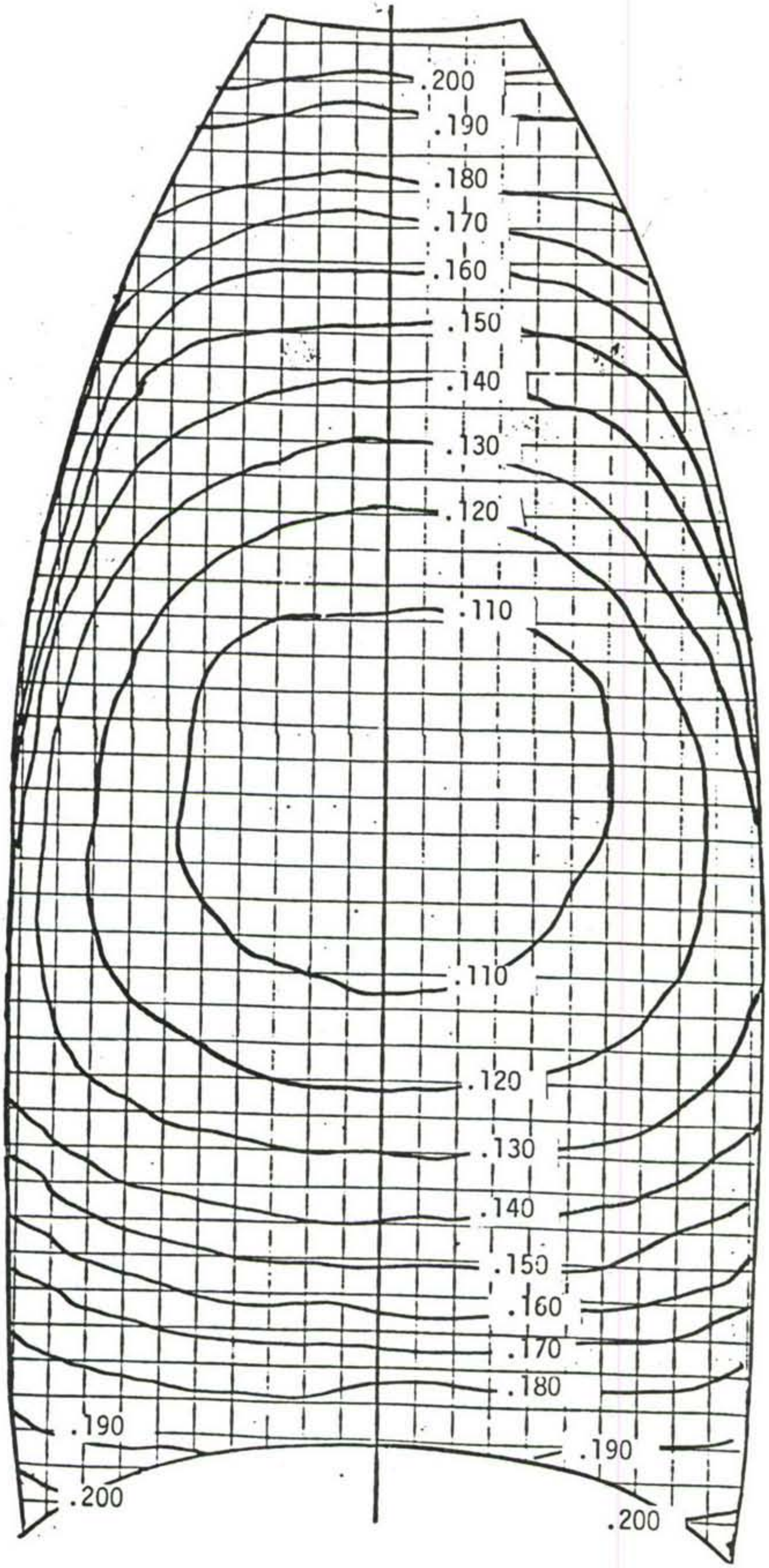


Figure 20. Average Thickness Map of Two Attempts #1 and #7
Uniform Thickness Blank
Uniform Temperature

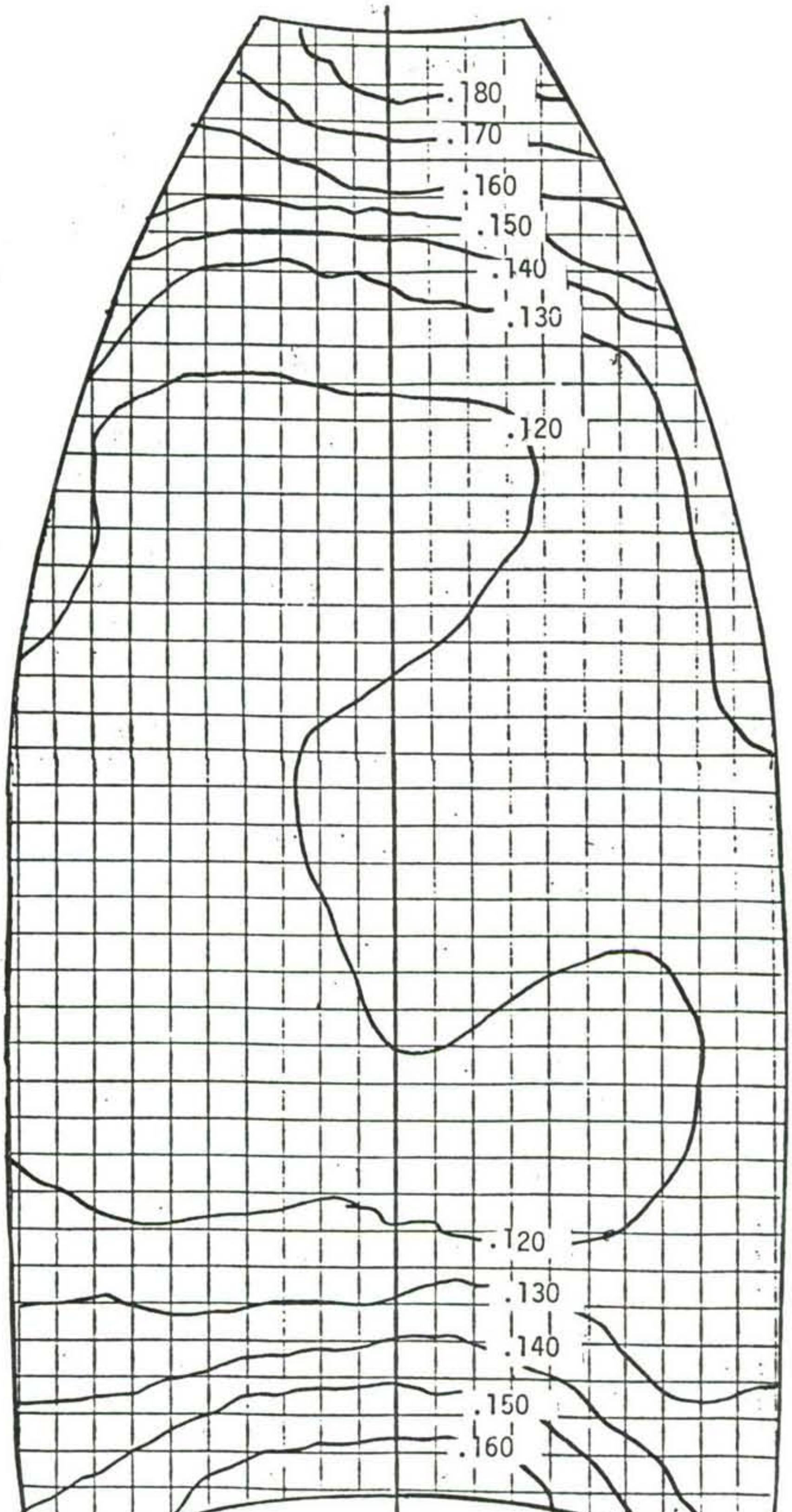


Figure 21. Final Thickness Map of Attempt No. 10
Variable Thickness Blank
Uniform Temperature

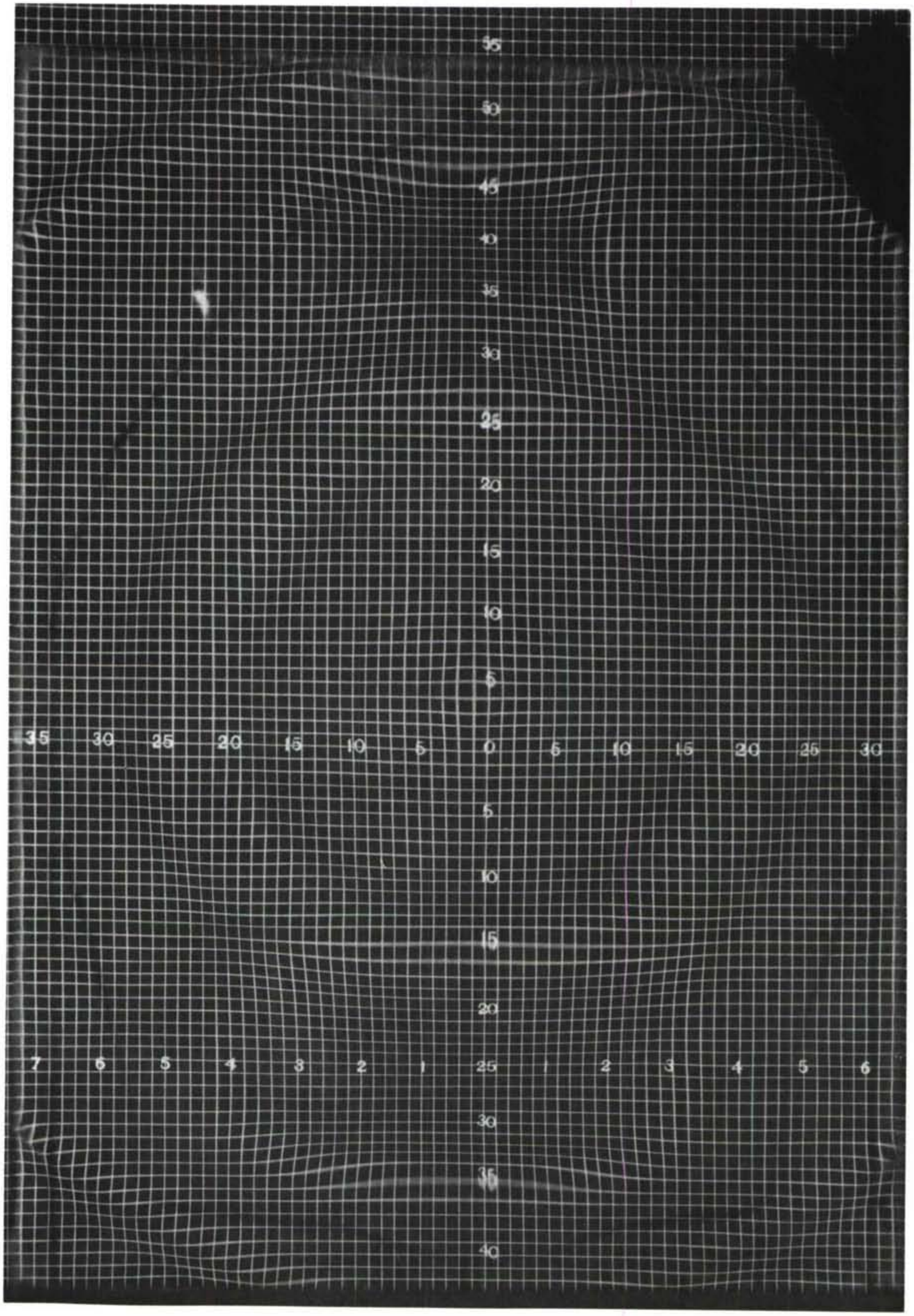


Figure 22. Variable Thickness Flat Blank Used in Attempt No. 11 Shown against a Gridboard

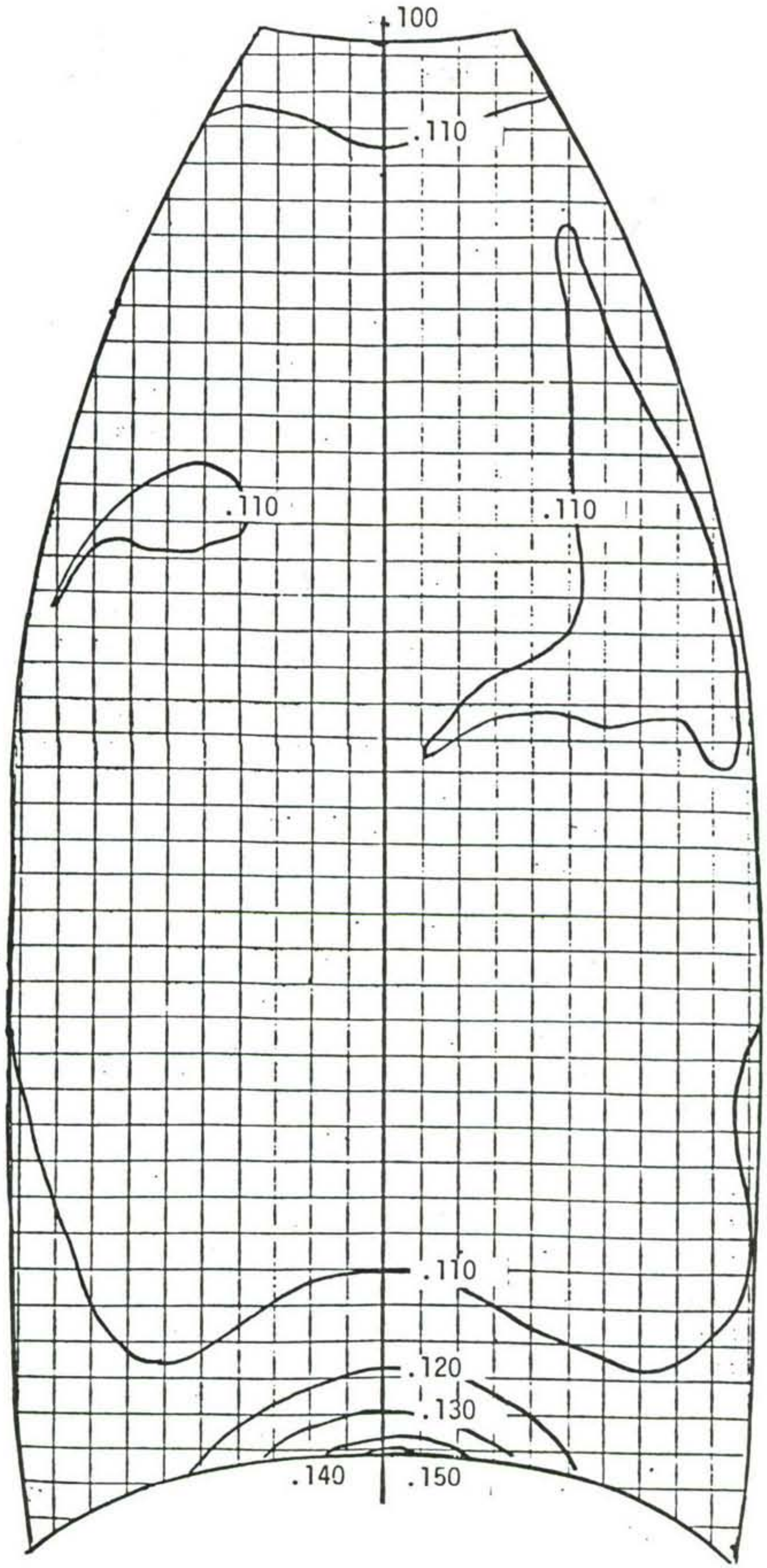


Figure 23. Final Thickness Map of Attempt No. 11
Variable Thickness Blank
Uniform Temperature

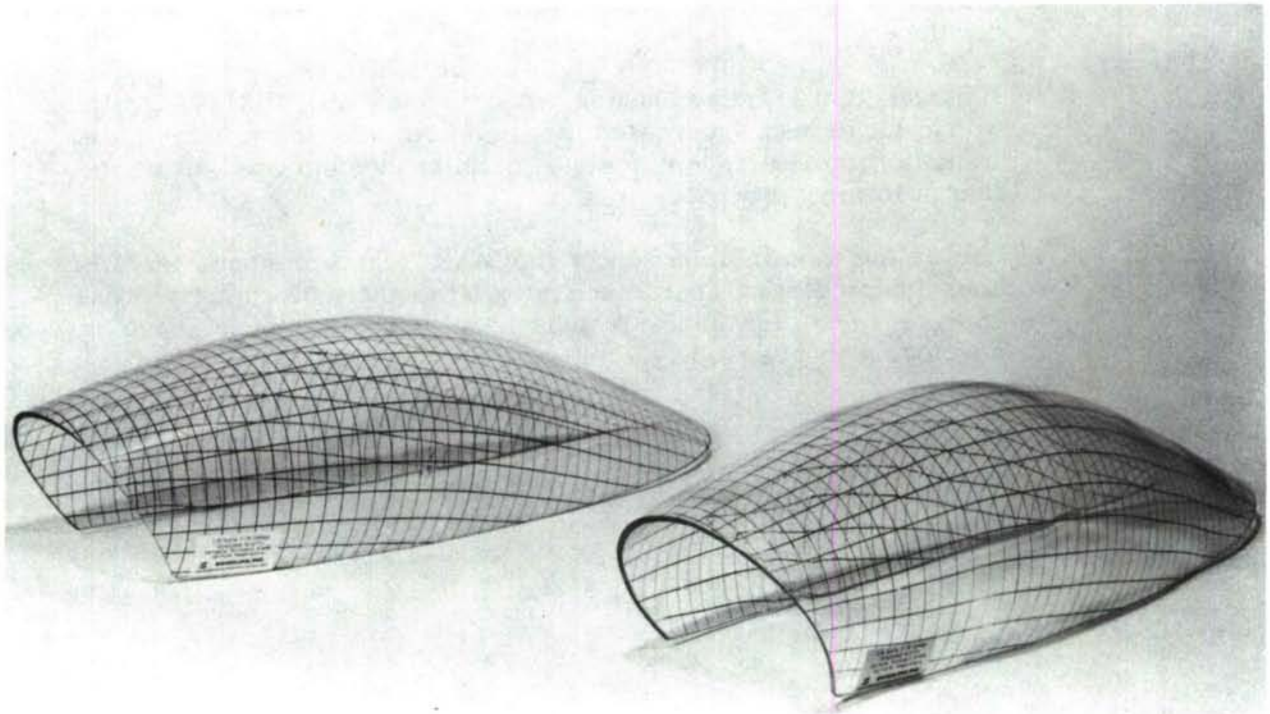


Figure 24. Two 1/4 Scale F-16 Canopy Transparencies (Attempts no. 6 and 10) Which Were Submitted to the US Air Force

SECTION VI

PROGRAM CONCLUSIONS

Four major conclusions were reached as a result of this program:

1. The feasibility of manufacturing uniform thickness stretched acrylic F-16 canopies from non-uniform thickness sheet stock has been demonstrated.

2. A method of testing uniaxial tensile specimens of thermoplastic materials above the glass transition temperature has been developed.

3. Uniaxial tensile stress-strain properties of MIL-P-8184 acrylic which have been generated at temperatures above the glass transition, are sufficient for use in finite element analysis of the thermoforming process.

4. Use of the modified version of the MARC finite element analysis code for predicting characteristics of the thermoforming process appears to be feasible. A substantial start has been made in developing this capability.

SECTION VII

RECOMMENDATIONS

The major benefits of this program were the development of manufacturing processes and testing the computer modeling feasibility for creating uniform thickness transparencies. This program has identified areas where more in-depth studies are desirable. These are described below.

1. Manufacture full-scale stretched acrylic F-16 canopies of uniform thickness for bird strike testing and to demonstrate other performance and cost values.

2. Continue to expand the characterization of acrylic at high temperatures.

3. Continue to develop the MARC code to deal with plastic thermoforming processes.

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